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Attention and Aviation Display Layout: Research and Modeling

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Final Technical Report
AHFD-05-21/NASA-05-8

December 2005

Prepared for

NASA Ames Research Center
Moffett Field, CA

Contract NASA NAG 2-1535

Abstract

This report overviews the work that was conducted on the grant NASA NAG 2-1535. Six general research thrust areas are described relating to addressing clutter effects, three dimensional displays, varying display size, comparing auditory and visual displays, using imperfect diagnostic automation, and modeling human attention and automation interaction. Each thrust area is associated with a set of research projects, whose contents are described in attached abstracts, and whose full contents can be accessed through http://www.humanfactors.uiuc.edu/research/TechReports/TechReports.asp.

Research Overview

This five year grant effort has focused on six interrelated research thrusts, that all address various issues related to displaying information to the pilot on the flight deck. To a considerable extent, we believe that the general issues addressed, and principles derived, are also applicable to a wider range of multi-task supervision and control environments. We describe these six thrusts below, referring as we do by number, to various technical reports supported by the grant, whose abstracts are presented in Appendix A of this report. Appendix B includes a listing of refereed articles published on the basis of this research.

1. **Approaches to addressing clutter**. Several reports have addressed the negative consequences of the desire to present large amounts of airspace information to the pilot related to traffic, weather and terrain hazards, as well as other required tasks [3, 5, 14, 16, 19]. An underlying theme of these projects relates to the tradeoffs between four sorts of display layouts: separate data bases displayed in adjacent panels, overlaid or integrated data bases with and without highlighting, and data bases that can be rendered or erased, one at a time in the same display region (e.g., multi-function displays, or “decluttered” displays). Each of these approaches has costs and benefits that are task and information dependent. Our research has attempted to identify these contingencies. For example it is acceptable to use a more cluttered overlaid display of two data bases if the task requires integration of those two, but not if it requires focused attention only on a single data base. Note that, while not covered in the current grant, this research is also quite relevant to the issue of what information to place on head up displays overlaying that information on the outside world (Wickens Ververs & Fadden, 2004).

2. **Display Dimensionality**. A large component of our research has focused on the advantages and costs of three dimensional displays (typically in contrast to co-planar 2D displays), an issue that flows from prior research supported by NASA (see Wickens, 2000). Within this broad topic one issue has focused in detail on properties of the 3D pathway or highway-in-the-sky (HITS) display, as a component of the synthetic vision system (SVS) display suite [1, 4, 16, 17, 19]. We ask what features make this a particularly valuable tool for flight path guidance: prediction, preview, or three-dimensional rendering of its depth along the track axis. This research has been closely related to a parallel effort carried out with support by NASA Langley (Alexander Hardy & Wickens, in press).

   A second issue has focused more directly on the strengths and weaknesses of 3D displays to support global hazard awareness, related to terrain and particularly to traffic, in the cockpit display of traffic information (CDTI) [4, 7, 12, 18. 19]. Such research has revealed that a major problem with such displays relates to their ambiguity [4] but an important feature to mitigate this problem is to provide rotatable versions of the displays [18].

3. Size and compression. Both of the above research thrusts involve display changes that influence either the size of the display, or the spatial resolution of displayed information. For example a “separated” side-by-side display philosophy addressed in [1] may require reducing the display size in half, relative to an integrated overlaid display. The three dimensional display, addressed in [2] will produce a compression along the depth axis, diminishing the size of displayed separations [4, 19]. In [14, 19] we have comprehensively looked at these and other manifestations of differing display size and resolution, as these modulate the readability and monitoring of displays, the perceived magnitude of displayed distances and deviations, and the implications for pilot judgment.

4. Display modalities. Several of our thrusts have contrasted auditory with visual delivery of specific verbal and alert information (within the context of the cockpit dominated by visual input) [10, 11, 17, 21]. This research not only answers practical questions of when it is appropriate to use voice synthesis or auditory alerts to present critical information, but also addresses the trade-off between two theories of cross modal presentation: multiple resource theory predicts that both tasks in a dual-task suite will be better served by cross modal presentation, whereas auditory preemption theory predicts that discrete information will benefit from an auditory presentation but this will capture or “preempt” attention to the detriment of an ongoing continuous visual task [10, 21]. Our research provides support for both theories, but illustrates the dominant role of multiple resources when sources of visual information are more widely separated.

5. Imperfect Automation . An ongoing theme addresses various forms of computer automation that can assist in displaying information. When such automation is of perfect reliability, its effects are generally to lower workload and improve performance. However our interest has been in the remaining benefits, as well as costs of automation known to be imperfect (i.e., reliability <1.0). Particular interest has focused on imperfect CDTI traffic conflict alerting, because of the inevitable lowering of reliability that results when conflicts are predicted over long look-ahead times [15, 21]. At issue here is not only the degree of residual benefit (over no alerts) even when the alert reliability is less than 1.0 [15], but also the influence of the threshold setting of the alert, in trading off “misses” (or late alerts) for false alerts [21].

6. Computational Modeling. Nearly all aspects of our research have fed into three forms of computational models, with relevance to display formatting and design.

6.1. Automation use. With [2] setting the stage for our understanding of cognitive effects of automation use, we have pursued a model of *automation dependence*, linking our effort in the present grant [15, 21] to a computational model of diagnostic automation dependence, and alert threshold setting in a parallel research effort on UAVs (Dixon & Wickens, in press; Wickens Dixon & Ambinder, 2006; Wickens & Dixon, in press).

6.2. Selective attention: The SEEV model. This model of how visual scanning is driven by **S**alience, **E**ffort, **E**xpectancy and **V**alue is described in [6] and [11]. A close cousin and derivative of the SEEV model is the Attention Situation Awareness (A-SA) model funded by a separate NASA grant (see Wickens McCarley et al., 2005, in press). Here the SEEV model describes scanning and information access necessary to support situation awareness and subsequent performance. The experiment reported in [16], while relevant to clutter and 3D issues described in [1] and [2] above, also generated visual scan data that were used to validate both SEEV and the A-SA model. One important derivative of our work on attentional modeling, has been the focus on the issue of *attentional tunneling* or attentional narrowing, leading to the failure to notice unusual or unexpected events (Wickens, 2005, [22]).

6.3. Display layout and the DFSAM model. The computational model that best integrates the majority of research described above is called the *Display formatting situation awareness model* (DFSAM) [20]. This model assumes that the net value of a particular display format is the linear sum of a series of "forces", such as clutter, size, dimensionality, and so forth, whose collective influence will yield the overall figure of merit for the display. In [21] the magnitude of these forces was derived from considering the collective results of the empirical studies described above (along with other prior NASA-supported work), and was then used to predict the net performance of different tasks in different conditions in the SVS simulation reported in [16] as a validation. This validation produced a strong correlation between predicted and observed performance scores.

List of Technical Reports (see Appendix A for Abstracts)

[1] Doherty, S. M., & Wickens, C. D. (2000). An Analysis of the Immersed Perspective Flight Path Display Benefit: Benefits of Preview, Prediction, and Frame of Reference (ARL-00-5/NASA-00-1).

[2] Wickens, C. D. (2000). Imperfect and Unreliable Automation and Its Implications for Attention Allocation, Information Access and Situation Awareness (ARL-00-10/NASA-00-2).

[3] Kroft, P., & Wickens, C. D. (2001). The Display of Multiple Geographical Data Bases: Implications of Visual Attention (ARL-01-2/NASA-01-2).

[4] Boeckman, K. J., & Wickens, C. D. (2001). The Resolution and Performance Effects of Three-Dimensional Display Rotation on Local Guidance and Spatial Awareness Measures (ARL-01-4/NASA-01-3).

[5] Podczerwinski, E. S., Wickens, C. D., & Alexander, A. L. (2002). Exploring the "Out of Sight, Out of Mind" Phenomenon in Dynamic Settings Across Electronic Map Displays (ARL-01-8/NASA-01-4).

[6] Wickens, C. D., Helleberg, J., Kroft, P., Talleur, D. A., & Xu, X. (2001). Mid Air Target Detection: What Makes it Difficult? Application of Attention and Situation Awareness Model (ARL-01-9/NASA-01-5).

[7] Alexander, A. L., & Wickens, C. D. (2001). Cockpit Display of Traffic Information: The Effects of Traffic Load, Dimensionality, and Vertical Profile Orientation (ARL-01-17/NASA-01-8).

[8] Muthard, E. K., & Wickens, C. D. (2001). Change Detection in a Flight Planning Task Environment: An Examination of the Confirmation Bias and Its Relation to Decision Making Errors (ARL-01-18/NASA-01-9).

[9] Wickens, C. D. (2002). Spatial Awareness Biases (ARL-02-6/NASA-02-4).

[10] Wickens, C. D., Dixon, S., & Seppelt, B. (2002). In Vehicle Displays and Control Task Interference: The Effects of Display Location and Modality (AHFD-02-7/NASA-02-5/GM-02-1).

[11] Wickens, C. D., Goh, J., Helleberg, J., & Talleur, D. A. (2002). Modality Differences in Advanced Cockpit Displays: Comparing Auditory and Vision for Navigational Communications and Traffic Awareness (ARL-02-8/NASA-02-6).

[12] Alexander, A. L., & Wickens, C. D. (2002). Does Traffic Load Modulate the Effects of Traffic Display Formats on Performance? (ARL-02-9/NASA-02-7).

[13] Muthard, E. K., & Wickens, C. D. (2002). Factors That Mediate Flight Plan Monitoring and Errors in Plan Revision: An Examination of Planning Under Automated Conditions (AHFD-02-11/NASA-02-8).

[14] Muthard, E. K., & Wickens, C. D. (2004). Compensation for Display Enlargement in Flight Control and Surveillance (AHFD-04-3/NASA-04-1).

[15] Xu, X., Wickens, C. D., & Rantanen, E. (2004). Imperfect Conflict Alerting Systems for the Cockpit Display of Traffic Information (AHFD-04-8/NASA-04-2).

[16] Wickens, C. D., Alexander, A. L., Thomas, L. C., Horrey, W. J., Nunes, A., Hardy, T. J., & Zheng, X. S. (2004). Traffic and Flight Guidance Depiction on a Synthetic Vision System Display: The Effects of Clutter on Performance and Visual Attention Allocation (AHFD-04-10/NASA(HPM)-04-1).

[17] Iani, C., & Wickens, C. D. (2004). Factors Affecting Task Management in Aviation (AHFD-04-18/NASA-04-7).

[18] Thomas, L. C., & Wickens, C. D. (2005). Effects of Display Dimensionality, Conflict Geometry, and Time Pressure on Conflict Detection and Resolution Performance Using a Cockpit Display of Traffic Information (AHFD-05-4/NASA-05-1).

[19] Muthard, E. K., & Wickens, C. D. (2005). Display Size Contamination of Attentional and Spatial Tasks: An Evaluation of Display Minification and Axis Compression (AHFD-05-12/NASA-05-3).

[20] Wickens, C. D. (2005). Display Formatting and Situation Awareness Model (DFSAM): An Approach to Aviation Display Design (AHFD-05-14/NASA-05-5).

[21] Colcombe, A. & Wickens, C.D. (2005). Cockpit Display of Traffic Information Automated Conflict Alerting: Parameters to Maximize Effectiveness and Minimize Disruption in Multi-Task Environments (AHFD-05-22/NASA-05-9).

[22] Wickens, C. D. (2005). Attentional Tunneling and Task Management (AHFD-05-23/NASA-05-10).

Appendix A. The Abstracts.

[1] Doherty, S. M., & Wickens, C. D. (2000). An Analysis of the Immersed Perspective Flight Path Display Benefit: Benefits of Preview, Prediction, and Frame of Reference (ARL-00-5/NASA-00-1).

A theoretical explanation for an immersed perspective flight path display is investigated in this current study. Past research suggests that the immersed perspective flight path display ("tunnel-in-the-sky") can improve flight path tracking when compared to more conventional flight navigation instruments but at present the specific sources of this benefit have not adequately been explained. On the basis of past research, four properties of the tunnel were investigated. These are egocentric frame of reference, preview of the flight path, prediction of future aircraft location, and a high display gain.

The four variables of frame of reference, preview, prediction, and display gain were experimentally contrasted in a partially crossed factorial design to investigate the relative contributions of each variable to the tunnel benefit. A quickened display condition was also included. Twenty-four subjects were asked to fly an aircraft through a series of vertically and laterally changing flight paths on a PC based simulation using eleven different displays incorporating the variables of interest. The dependent measures of root mean squared error in lateral and vertical tracking, mean number of resets, and mean number of control inputs were collected.

The results showed that preview benefits were greater than those of prediction. An interaction of prediction and preview was found, with the benefits of prediction sometimes being contingent on the presence of preview. Explanations of control order account for the finding that prediction and preview benefited lateral tracking more than vertical tracking. The egocentric frame of reference was found to play a large role in the tunnel benefit. This was especially true in conjunction with preview such that performance without a tunnel was benefited by an egocentric viewpoint. The large cost of an exocentric frame of reference was mediated by the paired presence of prediction and preview in the altitude data. The larger display gain appears to account for no portion of the egocentric frame of reference benefit.

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[2] Wickens, C. D. (2000). Imperfect and Unreliable Automation and Its Implications for Attention Allocation, Information Access and Situation Awareness (ARL-00-10/NASA-00-2).

In the first part of this report, four stages of information processing, -- attentional filtering, integration and inference, choice, and response execution, -- are outlined, each of which can be automated. Such automation can vary in its reliability. We distinguish between automation that is perfectly reliable, automation that fails "catastrophically" and automation whose reliability is high, but understandably imperfect (e.g., drawing inference from inherently ambiguous data or noisy sensors). In the case of imperfect automation, we also distinguish between cases when the operator is and is not aware of the imperfection. We then describe the various human performance costs resulting from these different states and levels of unreliability, as they are relevant to the different stages of automation. We emphasize empirical data from automated attention filtering (Stage 1) in such systems as target cueing alarms, or intelligent information management. Many of these costs relate to the distribution of attention in the environment. In the second part of the report, we then describe a model of the influences on how pilots distribute and allocate visual attention in dynamic environments, in order to maintain situation awareness. The model incorporates bottom up influences on attention allocation related to event salience and information access effort, and top-down influences related to habit, to the anticipated probability of information and to the value of that information. A more elaborate submodel of information access effort is presented.

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[3] Kroft, P., & Wickens, C. D. (2001). The Display of Multiple Geographical Data Bases: Implications of Visual Attention (ARL-01-2/NASA-01-2).

This experiment addresses the issues faced by a designer who must display to the pilot multiple complex spatial data bases, such as those pertaining to traffic, terrain, and weather. Five plausible design solutions for two data bases (traffic/weather and terrain) are compared: (1) Separated displays, side-by-side. (2) Integrated, overlaid display. (3) Overlay with intensity coding to aid discrimination of the data bases. (4) Overlay with pilot-controlled interaction to apply intensity coding as needed. (5) Overlay with pilot controlled interaction to declutter (erase) data bases as needed. An additional 6th condition was included to determine whether the potential advantage of (2) (overlay) over (1) (separated) was a consequence of the integration in (2), or the larger text size of a single display, compared with two side-by-side displays occupying the same total area as the single display. Fifteen general aviation pilots answered a series of questions that required integration across data bases, or focused attention within a single data base.

The results are interpreted in the context of a model of information processing that identifies costs and benefits of different information processing mechanisms related to visibility, divided, focused and selective attention, whose influence is varied as the display conditions are contrasted. These results revealed that the combined costs of scanning and small display size of (1) clearly dominate the smaller cost of clutter from display overlay in (2). The benefits of overlay are greatest when questions require integration of information between data bases. Lowering the intensity of one of the data bases in (3) offers no benefits to the clutter caused by overlay because of difficulty decoding the lower intensity information. Interactivity in (4) and (5) imposes time costs which do not generally outweigh the benefits provided of allowing the focus of attention on one data base at a time by lowlighting or erasing the irrelevant data base respectively. However under some circumstances there are benefits of full decluttering (5) on the focus of attention.

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[4] Boeckman, K. J., & Wickens, C. D. (2001). The Resolution and Performance Effects of Three-Dimensional Display Rotation on Local Guidance and Spatial Awareness Measures (ARL-01-4/NASA-01-3).

This study examined the common and distinct perceptual\cognitive mechanisms between spatial judgments and flight path tracking, as the azimuth and elevation angle of a 3D flight path display was varied. Pilots flew a multi-leg mission on a computer simulated aircraft, adhering to the flight path and making judgments of the azimuth, elevation and distance of targets that appeared at unexpected times and locations, relative to ownship. The results indicated that changes in the viewing angle away from that along the flight path of the display increased both tracking error (along the changed axis -- elevation or azimuth), and judgment error, but these increases followed different functions of angle between the two axes and between the two tasks. In all cases the loss of resolution while viewing along the line-of-sight into the display was implicated. But the effect harmed tracking error more than spatial judgment error. An additional component related to the incongruent display-control compatibility influenced only tracking error (not judgment error), but did so more for lateral than for vertical viewpoint rotation, because vertical rotation preserved a natural "forward-up" association. Finally, there was some evidence that 45 degree offsets in both axes preserved the best collective judgments across both axes. Distance judgments were most rapid at these values, and tracking performance was less effected. The results are discussed in terms of their task-dependent implications for 3D aviation displays.

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[5] Podczerwinski, E. S., Wickens, C. D., & Alexander, A. L. (2002). Exploring the “Out of Sight, Out of Mind” Phenomenon in Dynamic Settings Across Electronic Map Displays (ARL-01-8/NASA-01-4).

This study compared highlighting benefits and decluttering costs of electronic map design in dynamic settings and examined the potential cost of the “out of sight-out of mind” or OOSOOM phenomenon in decluttering conditions. This phenomenon describes the particular vulnerability to noticing that things have changed, when a display was not in view at the time of the change. Sixteen pilots flew a simulated aircraft for eight trials using baseline, traffic highlighted, traffic lowlighted, and manual decluttering displays. They answered focused and divided attention questions, detected changes in the trajectory of traffic and weather, and avoided conflict events by maneuvering vertically. Results revealed that the traffic highlighting display was the overall best display for lateral flight path tracking and for detecting heading changes. Change detection was only at 50% accuracy, but improved by changes that were more salient (spatially, not digitally represented), and were more meaningful (causing a conflict with the flight path). Change detection was only slightly influenced by the distance of the change from the pilot’s focus of attention on ownship. The decluttered display imposed a cost on detecting salient changes, a likely manifestation of the OOSOOM effect. This effect was also reflected in the lower accuracy of detecting changes when they were not in a displayed database at the time of their occurrence.

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[6] Wickens, C. D., Helleberg, J., Kroft, P., Talleur, D. A., & Xu, X. (2001). Mid Air Target Detection: What Makes it Difficult? Application of Attention and Situation Awareness Model (ARL-01-9/NASA-01-5).

This short report integrates the data that have been collected across three experiments in a high fidelity flight simulator in which traffic has been visible in the outside world, and visual scanning has been measured. The goal was to obtain data on the relation between visual attention allocation, traffic visibility, the automation guidance offered by a CDTI, and traffic detection performance. Large differences in such performance were observed, and attributed particularly to differences in traffic conspicuity, automation guidance, task priorities and pilot's attention allocation strategies. The results are compared with commonly advocated guidance for outside scanning in pilot training manuals.

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[7] Alexander, A. L., & Wickens, C. D. (2001). Cockpit Display of Traffic Information: The Effects of Traffic Load, Dimensionality, and Vertical Profile Orientation (ARL-01-17/NASA-01-8).

Eighteen certified flight instructors from the University of Illinois Institute of Aviation participated in an experiment exploring the design of the Cockpit Display of Traffic Information for free flight. Pilots flew a sequence of flight scenarios to compare the effects of traffic load, dimensionality, and orientation of the vertical profile view on a coplanar display on maneuver frequency, safety, and maneuver efficiency. Climbs and descents were found to be more frequent than other maneuvers. Climbs were specifically more common with the 2D coplanar displays while descents were more common with the 3D display. Both the rear-view and 3D displays were safer in terms of predicted conflict avoidance than was the side-view display. Climbing maneuvers were more safely implemented with the rear-view and 3D displays than with the side-view display. Altitude maintenance of lateral/vertical maneuvers was best with the side-view, then the rear-view, and then poorest with the 3D display. Airspeed efficiency of airspeed maneuvers was best with the rear-view display. Subjective workload was found to be highest with the 3D display, significantly lower with the side-view display, and lowest with the rear-view display. Collectively, these findings suggest that a rear-view coplanar CDTI may be preferable to either a side-view coplanar or 3D display.

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[8] Muthard, E. K., & Wickens, C. D. (2001). Change Detection in a Flight Planning Task Environment: An Examination of the Confirmation Bias and Its Relation to Decision Making Errors (ARL-01-18/NASA-01-9).

The purpose of this study was to examine how change detection affects a pilot's enroute flight planning task ability. Pilots were asked to choose between two flight paths that traversed through hazardous airspace. After the flight path choice was made, pilots then monitored this airspace for the purpose of seeking cues and detecting changes, and then, if necessary, revising the initial flight plan choice at two points along the flight path. Automated aids, consisting of highlighted hazards and recommended path choices were provided for the pilots. Results indicate that change detection is affected by both data-driven and contextually-driven factors, but more so by the latter. Findings provide little indication of the existence of the confirmation bias that may have led some pilots to continue traveling on a flight path that had become unsafe. Path choice performance was more accurate, and confidence ratings were higher, for simple than for difficult path choices, and no benefit for automation was found.

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[9] Wickens, C. D. (2002). Spatial Awareness Biases (ARL-02-6/NASA-02-4).

Pilot performance models used for representing task demands with new display technology, such as Synthetic Vision Systems, should benefit from a module associated with spatial awareness. Such a module represents how the pilot understands his/her position and trajectory in the 4D space (X, Y, Z and time), with regard to the desired flight path and waypoints, and with regard to terrain, traffic and weather hazards.

This paper reviews and integrates the biases that have been documented through research in how the pilot's representation is influenced by features of the display of visual-spatial information. These biases can then be incorporated into such a model.

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[10] Wickens, C. D., Dixon, S., & Seppelt, B. (2002). In Vehicle Displays and Control Task Interference: The Effects of Display Location and Modality (AHFD-02-7/NASA-02-5/GM-02-1).

In-vehicle displays, whether in aircraft or in ground vehicles, can often divert visual attention away from critical information for vehicle path monitoring and control (i.e., tracking). This experiment compares two proposed solutions to this attention competition: (1) changing the location of the display, by moving it closer to the locus of tracking information, ultimately to a superimposed head up (HUD) position, and (2) changing the modality of presentation from visual to auditory. Twenty-four participants performed a 2 axis first order compensatory tracking task, while a simulated in-vehicle task of encoding and vocally responding to digit strings of various lengths was presented at unpredictable times. The digit side task could be presented at a HUD location, at any of 4 separations to the right of the tracking task, ranging from adjacent (7.5 degrees) to 45 degrees of visual angle, at any of two locations below the tracking task, or through the auditory modality.

The results revealed that: (1) auditory delivery of side task information "preempted" the tracking task, to the advantage of the side task, but at the cost of tracking performance; (2) spatial overlay (HUD) decreased the readability of the side task, with a small cost to tracking; (3) spatial separation at small visual angles had costs to both detecting the side task onset and tracking error. These costs were greater when displacement was downward than when it was leftward; and (4) greater eccentricity displacements delayed the initiation and completion of the side task response and, in particular, increased tracking error while the digit string responses were vocalized. Side task load varied by digit string length and generally had additive effects with display location.

Measures of tracking control activity were employed to diagnose the nature of the interfering effects. The results are interpreted in terms of their relevance to single channel theory, multiple resource theory, task switching theory, and theories of visual attention allocation.

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[11] Wickens, C. D., Goh, J., Helleberg, J., & Talleur, D. A. (2002). Modality Differences in Advanced Cockpit Displays: Comparing Auditory and Vision for Navigational Communications and Traffic Awareness (ARL-02-8/NASA-02-6).

Twelve pilots flew a full mission simulation to examine two aspects of advanced aviation display technology: digital datalink, and the cockpit display of traffic information (CDTI). Aviation performance with both of these information sources displayed in both visual formats was compared with performance when equivalent information was displayed auditorally (mimicking either air traffic control or a synthesized voice display) and redundantly combining both modalities. In addition, the effectiveness of different pilot visual scanning strategies, in spotting outside traffic was examined, in conjunction with the attention guidance offered by either CDTI or ATC support.

Flight path tracking was disrupted by higher outside traffic load, and by the visual display of both CDTI and data link information relative to the auditory display. This disruption was a consequence of the visual attention demands of these devices, which pulled attention away from viewing the outside horizon., and led to shorter dwells on the instrument panel. Outside traffic was detected at around a 90% rate. Traffic detection was not generally helped by the more precise guidance offered by the CDTI, and was slightly hurt by the visual attention (head down) demands of the CDTI, particularly when such traffic was not represented in the CDTI data base. Pilots generally protected their scanning to the instrument panel, from the increased demands of other concurrent task elements. The comprehension of longer communications strings suffered slightly from the delivery of auditory ATC information. The redundant display failed to provide better performance across the collective tasks of aviating (flight path control), navigation (traffic detection) and communications (ATC message comprehension) than the best of the single modality conditions, and was inferior to these in terms of disrupting altitude control.

A variety of outside scan patterns were identified, and the “sector sweep” pattern appeared to be most proficient, both in terms of detecting traffic, and minimizing disruption of the flight task. The results are interpreted in terms of multiple resource and selective models of pilot attention, and of S-C-R compatibility.

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[12] Alexander, A. L., & Wickens, C. D. (2002). Does Traffic Load Modulate the Effects of Traffic Display Formats on Performance? (ARL-02-9/NASA-02-7).

The FAA and NASA have recently undertaken a research effort to examine specific ways to improve efficiency of the National Airspace System. Eighteen certified flight instructors from the University of Illinois Institute of Aviation participated in an experiment exploring the design of the Cockpit Display of Traffic Information for free flight traffic avoidance maneuvers. Pilots flew a sequence of flight scenarios to compare the effects of traffic load, dimensionality, and a vertical profile orientation on maneuver frequency, conflict avoidance performance, and maneuver efficiency. The highest levels of workload induced more combined lateral/vertical maneuvers, degraded safety on the coplanar displays, and degraded efficiency regardless of display type. In the context of an overwhelming preference for vertical maneuvers, the 3D display increased the frequency of the less-safe descent maneuvers (relative to climbs) and increased subjective workload, while the 2D rear-view display decreased the vertical efficiency of all maneuvers, relative to its side-view counterpart. The results are interpreted within the context of an information processing model of situation assessment and choice.

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[13] Muthard, E. K., & Wickens, C. D. (2002). Factors That Mediate Flight Plan Monitoring and Errors in Plan Revision: An Examination of Planning Under Automated Conditions (AHFD-02-11/NASA-02-8).

The present experiment sought to explore the effects of automation on plan monitoring and errors in plan revision. Pilots were asked to select one of two flight paths that traversed through hazardous airspace with the aid of attention guidance automation, then monitor the safety of this plan by seeking and reporting changes in dynamic traffic aircraft and weather systems. In one-fourth of trials, an experimenter-induced change threatened the safety of the chosen flight path, and pilots should have optimally revised their plan as a result. In these trials, the automation always failed to highlight this hazard, despite its increase in both its importance to the planning task and its risk to the safety of the flight plan. A secondary loading task was added on all trials. Automation aided plan selection accuracy and secondary task performance. Pilots were poor at plan monitoring, detecting only 30.5% of changes, which is substantially less than that found in a similar, though less demanding version of this experiment. Changes that were relevant to the planning task were detected more quickly than irrelevant changes, and changes to highlighted hazards were more accurately detected than those to non-highlighted hazards. Pilots committed plan continuation errors on nearly one-third of trials, and were more likely to do so under the imperfect automation condition than with no aid present. A relationship between the likelihood of committing a plan continuation error and performance in detecting the change that threatened the safety of the flight path was also found, showing that, in those trials where pilots failed to properly revise a plan, detection of the safety-threatening change was also poorer.

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[14] Muthard, E. K., & Wickens, C. D. (2004). Compensation for Display Enlargement in Flight Control and Surveillance (AHFD-04-3/NASA-04-1).

Two experiments were conducted to assess the impact of display size on flight control, airspace surveillance, and goal-directed target search. In Experiment 1, 16 pilots completed a basic flight control task under single and dual axis control. Pilots exhibited less path error and greater stick activity with a large-scale display, suggesting that larger depictions of error lead to greater urgency in correcting deviations. Experiment 2 scaled-up findings from Experiment 1 for flight control, hazard surveillance, and target search tasks. Results from Experiment 1 were replicated for the flight control task. Size, however, did not affect surveillance or search because pilots were adaptive in altering scanning patterns in response to increases in display size. Practical implications of these results are that displays should not be minified to fit within cramped cockpits, as such changes will hinder flight control.

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[15] Xu, X., Wickens, C. D., & Rantanen, E. (2004). Imperfect Conflict Alerting Systems for the Cockpit Display of Traffic Information (AHFD-04-8/NASA-04-2).

This experiment assessed pilots' abilities to use the imperfect (partially reliable) alerting system to detect conflicts on a cockpit display of traffic information (CDTI). An 83% reliability level of automated conflict detection that was chosen, simulated the sort of unreliability that might be characteristic of such a system, predicting conflicts with longer look-ahead-times, in a probabilistic airspace, subject to turbulence, uncertainty, and future pilot control actions between the time of alert and the time of closest approach with the conflicting traffic.

24 licensed pilots viewed a series of dynamic encounters on a 2D CDTI that varied widely in their difficulty, as influenced by lateral conflict geometry (conflict angle, speed, and distance & time till closest approach). Pilots were asked to estimate the point and time of closest approach at varying times before that point was reached. A 3-level alert system provided a correct categorical estimate of the projected miss distance on 83% of the trials. The remaining 17% of alerts were equally divided between automation misses and false alarms, of large and small magnitude. The data of these pilots were compared with a matched sample of "baseline" pilots who viewed identical trials without the aid of automated alerts.

The results revealed that roughly half the pilots depended on automation, and used it to improve their performance (accurate estimation of miss distance) relative to the baseline pilots who did not receive the automation. Those pilots who depended on automation did so more on the more difficult traffic trials, and were able to improve their performance on the 83% trials when automation was correct, without causing harm (relative to the non-automated group) on the 17% of automation-error trials. The presence of automated alerts appeared to lead pilots to inspect the raw data more closely. Pilots did not appear to be differentially hurt by automation misses versus false alerts. There was some evidence that the presence of automation, while assisting the accurate prediction of miss distance, led to an underestimation of the time remaining till the point of closest approach. The results point to the benefits of even imperfect automation in the strategic alerts characteristic of the CDTI, at least as long as this reliability remains high (above 80%).

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[16] Wickens, C. D., Alexander, A. L., Thomas, L. C., Horrey, W. J., Nunes, A., Hardy, T. J., & Zheng, X. S. (2004). Traffic and Flight Guidance Depiction on a Synthetic Vision System Display: The Effects of Clutter on Performance and Visual Attention Allocation (AHFD-04-10/NASA(HPM)-04-1).

Fourteen pilots flew a synthetic vision system (SVS) display through a terrain and traffic-rich environment in a high fidelity flight simulator. Traffic information was hosted on the SVS display. In a 2x2 factorial design, the SVS display hosted a highway-in-the-sky in half the conditions, while instrument panel information and a flight path velocity vector was the sole means for guidance in the other conditions. In half the trials the instrument panel overlaid the SVS display, and in the other half it was separate, allowing us to examine the effects of the resulting clutter. Tunnel guidance, and clutter effects were examined as they influenced routine flight performance, SVS traffic detection and change awareness, and the pilots' response to off-normal events, as these were mediated by visual scanning measures of attention allocation. The tunnel greatly improved flight path tracking and detection of traffic on the SVS display, and did not hurt the detection of traffic changes present on a CDTI. However the tunnel disrupted the detection of the two off-normal events: unexpected outside world traffic, and of a runway offset. The instrument panel overlay provided no benefits to tracking and a clutter-related time cost to SVS traffic detection. Scanning analysis on 8 of the pilots revealed that visual attention was focused on the SVS display over half the time, and rarely on the outside world, even in visual meteorological conditions (VMC). This scanning pattern indicated a source of possible cognitive tunneling. However in general, scanning was not tightly linked to performance. The final section of this report describes our efforts to apply a computational model to predict the visual scanning data.

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[17] Iani, C., & Wickens, C. D. (2004). Factors Affecting Task Management in Aviation (AHFD-04-18/NASA-04-7).

The present paper summarizes the results of a study investigating task management and task prioritization processes in aviation. Forty instrument rated pilots flew three curves approaches in a high fidelity simulation using a Synthetic Vision System (SVS) display. In addition to the primary task of flying, during the last approach they were required to select the approach path on the basis of environmental information concerning weather. The level of immersion in the task, the nature, and saliency of the cues signaling the need to divert attention to the path selection task and the cost of not performing the secondary task were manipulated to investigate their influence on task prioritization. We found that cue saliency affected the frequency of the switch to the secondary task. Furthermore, pilots flying with the immersive display (tunnel display) were more likely to detect the change in the weather and were easily interrupted by the secondary task when priority was high. In terms of practical implications, the current results support the utility of the flight path tunnel display and suggest that some of the concerns, regarding the negative consequences of its compelling nature, may not be as pronounced as once thought.

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[18] Thomas, L. C., & Wickens, C. D. (2005). Effects of Display Dimensionality, Conflict Geometry, and Time Pressure on Conflict Detection and Resolution Performance Using a Cockpit Display of Traffic Information (AHFD-05-4/NASA-05-1).

Cockpit displays of traffic information (CDTIs) are intended to support pilots' ability to perform en route tasks such as conflict detection and resolution. Three experiments were designed to investigate the effects of CDTI display dimensionality as well as the conflict geometry and time pressure of in-flight conflicts on the performance of these tasks. Pilots were assigned to one of three display conditions: a 2-D Coplanar display combining a top-down and side view, a 3-D Toggle display with two available fixed perspective views, and a 3-D Manipulable display where pilots continuously controlled the viewpoint. Experiment 1 presented simple conflicts where an intruder was predicted to conflict with the pilot's ownship in 5 minutes from the start of the trial. Experiment 2 presented a subset of conflict trials from Experiment 1 with 5 additional traffic aircraft (not in conflict with ownship or intruder). Half of these trials included conflicts predicted to occur in 2 minutes (high time pressure). Pilots in Experiment 2 were also required to perform a concurrent tracking task. Experiment 3 presented pilots with a series of trials where the task was to determine whether a conflict existed between ownship and the intruder.

The results of all three experiments indicated that the interactive features included in the two 3-D displays were sufficient to reduce and essentially eliminate previously reported ambiguity costs, compared to the 2-D Coplanar display. All three displays demonstrated vulnerability to increased workload. In addition, with increasing workload the two 3-D displays, but not the 2-D, showed an increased preference for lateral maneuvers, which were less safe than vertical. Increased time pressure resulted in an increase in vertical maneuvers, (an effect limited to the two 3-D displays). In addition, the 2-D Coplanar display produced the most efficient resolution flight paths. Together, these results suggest that the 2-D Coplanar display is the best for the resolution task. Further, although conflict detection performance rates and response times between the 2-D Coplanar and 3-D Manipulable are equivalent, pilots using the 3-D display demonstrated overconfidence in their responses, while pilots using the 2-D display appeared to be better calibrated to their own performance. Thus the 2-D Coplanar display is slightly preferable for the detection task as well.

The most difficult conflict geometries for both tasks were those where one or both aircraft were making vertical changes and were approaching from close physical locations (overtake scenarios). These geometries are particularly difficult because the changes occur in all three spatial dimensions, making it harder to create a solution path, and a slower closure rate, leading pilots to make errors in extrapolating the planes' relative positions (for detection).

Pilots demonstrated the same preferences for vertical maneuvers over lateral (in low workload) and climbs over descents for level-flight conflicts that have been observed in previous research. These preferences may be incorporated into automated resolution algorithms to better ensure pilot acceptance of computer-generated resolution maneuvers.

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[19] Muthard, E. K., & Wickens, C. D. (2005). Display Size Contamination of Attentional and Spatial Tasks: An Evaluation of Display Minification and Axis Compression (AHFD-05-12/NASA-05-3).

Four experiments were conducted to evaluate the influence of display size on attentional and spatial tasks. In Experiments 1 and 2, display size was manipulated by enlarging the physical size of a top-down 2D integrated hazard display. Pilots were asked to monitor the airspace for changes in the trajectory or altitude of traffic aircraft or weather systems. In Experiment 1, pilots were also asked to periodically search the airspace for key hazards. In Experiment 2, this probe task was removed to examine surveillance unconfounded by search and display clutter was added. In both experiments, pilots were found to consistently adjust scanning patterns to account for an enlargement of the display area, and thus the area to be monitored. While change detection performance was worsened for events occurring near the display periphery, this effect was not amplified when the display was enlarged. Search was also unaffected by display size. For experiment 2, clutter reduced detection performance in the smallest display, where display density was amplified because of the minification. In Experiment 3, pilots were asked to complete a compensatory tracking task with a simplified flight control display. Display size was manipulated by changing the physical size of a 2D display and through axis compression in a 3D display. In both cases, pilots were found to exhibit higher tracking error and lowered control activity when display size was reduced, and this effect was amplified for axis compression. This performance reduction was hypothesized to have resulted both from the lowered resolution of the smaller display, which provided less information about small deviations than its larger counterpart, and from reduced urgency, as pilots perceived the smaller *displayed* errors as less severe path deviations. Finally, in Experiment 4, pilots were asked to select one of two flight paths that traversed through a hazardous airspace, as well as rate the safety of the flight paths. The size of the integrated hazard display was again manipulated by reducing the physical size of the 2D display or through axis compression of the 3D display. Results indicated that pilots were more likely to overestimate the span between their own aircraft and environmental hazards when this distance was portrayed on a large display, regardless of the means through which size was manipulated. When display size was manipulated through axis compression, this overestimation translated into an unsafe route choice. Analyses suggest that display enlargement can be made without imposing detrimental effort costs to attentional tasks, but spatial estimates become biased by display scale and influence resultant flight control and route selection tasks.

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[20] Wickens, C. D. (2005). Display Formatting and Situation Awareness Model (DFSAM): An Approach to Aviation Display Design (AHFD-05-14/NASA-05-5).

We describe a computational model, Display Formatting and Situation Awareness (DFSAM) that is designed to predict a figure of merit for an aviation display that has any of eight objectively quantifiable or definable features, such as its dimensionality (2D or 3D), clutter, or size. A set of 46 different experimental results (effect size estimates), and two meta analyses, extracted from 25 different studies conducted at University of Illinois, are analyzed and aggregated to estimate the net cost or benefit of the effect in question. These costs/benefits are referred to as **amalgamated performance units** (APUs). The APUs can then be combined for any particular display to predict its figure of merit, and the *difference* in figure of merit from any other display. The model is validated against the data from a high fidelity synthetic vision simulation, conducted with four different display formats, and was found to predict multitask flight control performance (r =0 .89) and traffic awareness response time (r = 0.81) and accuracy (r = 0.96). Constraints and limits of the model are discussed.

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[21] Colcombe, A. & Wickens, C.D. (2005). Cockpit Display of Traffic Information Automated Conflict Alerting: Parameters to Maximize Effectiveness and Minimize Disruption in Multi-Task Environments (AHFD-05-22/NASA-05-9).

Student pilots participated in a series of four experiments to examine conflict alerting systems to augment the cockpit display of traffic information in a dual task context. At issue was the nature of task management and task switching, and how this was influenced by the modality of the alert, the level of resolution of the alert (likelihood 3-stage vs. binary 2-stage), the threshold setting of the alert, and the nature of the concurrent task. Across all four experiments the binary alert was generally more effective than the likelihood alert, and the auditory alert generally supported better conflict detection response than did the visual alert. However the impact of modality on the concurrent task was modulated by the nature of that task (visual tracking was more disrupted by the auditory alert). Variation of alert threshold between experiments indicated that false alarm prone automation delayed response to the alert, whereas miss-prone automation degraded the concurrent task. The results are interpreted in the context of theories of task management and task switching, and of theories of automation dependence.

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[22] Wickens, C. D. (2005). Attentional Tunneling and Task Management (AHFD-05-23/NASA-05-10).

This paper discusses attentional tunneling as one cause of breakdowns in task management. The phenomenon is defined, and empirical evidence is then reviewed to show the conditions in which the phenomenon is created by head up display location, compelling 3D displays, fault management, and automation induced complacency. Statistical and methodological issues are reviewed regarding the generalization of the phenomenon in the laboratory to real world mishaps.

Appendix B. Refereed Publications Support by Grant.

Refereed articles and book chapters (* = not supported by grant, but referred to in the text)

* Alexander, A., Wickens, C. D., & Hardy, T. J. (in press). Synthetic vision systems: The effects of guidance symbology, display size, and field of view. *Human Factors*.

Alexander, A. L., Wickens, C. D., & Merwin, D. (2005). Perspective and Co-planar cockpit display of traffic information: implications for maneuver choice, flight safety and mental workload. *International Journal of Aviation Psychology, 15*(1), 1-21.

* Dixon, S. R., & Wickens, C. D. (in press). Automation reliability in unmanned aerial vehicle flight control: Evaluating a reliance-compliance model of automation dependence in high workload. *Human Factors*.

Iani, C., & Wickens, C. D. (in press). Factors affecting task management in aviation. *Human Factors*.

Kroft, P., & Wickens, C. D. (2003). Displaying multi-domain graphical database information: An evaluation of scanning, clutter, display size, and user interactivity. *Information Design Journal*, *11*(1), 44-52.

Muthard, E. & Wickens, C. D. (2005, in press). Pilots strategically compensate for display enlargements in surveillance and flight control tasks. *Human Factors.*

Wickens, C. D. (2003). Pilot actions and tasks: Selection, execution, and control. In P. Tsang and M. Vidulich (Eds.), *Principles and practice of aviation psychology* (pp. 239-263). Mahwah, NJ: Lawrence Erlbaum Publishers.

Wickens, C. D., Alexander, A. L., Ambinder, M. S., & Martens, M. (2004). The role of highlighting in visual search through maps. *Spatial Vision*, *37*, 373-388.

Wickens, C. D., Ververs, P., & Fadden, S. (2004). Head-up display design. In D. Harris (Ed.), *Human factors for civil flight deck design* (pp. 103-140*)*. UK: Ashgate.

Wickens, C. D., Vincow, M., & Yeh, M. (2005. Design applications of visual spatial thinking: The importance of frame of reference. In A. Miyaki & P. Shah (Eds.), *Handbook of visual spatial thinking*. Oxford University Press.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science*, 3(2), 159-177.

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* Wickens, C. D., & Dixon, S. R. (in press). Is there a magic number 7 (to the minus 1)? The benefits of imperfect diagnostic automation: A synthesis of the literature. *Theoretical Issues in Ergonomics Science*.

* Wickens, C. D., Dixon, S. R., & Ambinder, M. S. (2006). Workload and automation reliability in unmanned air vehicles. In N. J. Cooke, H. Pringle, H. Pedersen & O. Connor (Eds.), *Advances in human performance and cognitive engineering research, Vol. 7, Human factors of remotely operated vehicles* (pp. 209-222). Elsevier Ltd.

Wickens, C. D., Goh, J., Helleberg, J, Horrey, W., & Talleur, D. A. (2003). Attentional models of multi-task pilot performance using advanced display technology. *Human Factors, 45*(3), 360-380.

* Wickens, C. D., McCarley, J. S., Alexander, A., Thomas, L., Ambinder, M., & Zheng, S. (2005, in press). Attention-Situation Awareness (A-SA) model of pilot error. In D. Foyle & B. Hooey (Eds.), *Pilot performance models*. Lawrence Erlbaum.

* Wickens, C. D., Ververs, P., & Fadden, S. (2004). Head-up display design. In D. Harris (Ed.), *Human factors for civil flight deck design* (pp. 103-140). Ashgate.

Xu, X., Wickens, C. D., & Rantanen, E. M. (submitted). Effects of conflict alerting system reliability and task difficulty on pilots' conflict detection with cockpit display of traffic information. *Ergonomics*.

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Alexander, A. L., & Wickens, C. D. (2002). Does workload modulate the difference between cockpit traffic display formats? *Proceedings of the 46th Annual Meeting of the Human Factors and Ergonomics Society*. Santa Monica, CA: Human Factors & Ergonomics Society.

Alexander, A. L., & Wickens, C. D. (2003). The effects of spatial awareness biases on maneuver choice in a cockpit display of traffic information. *Proceedings of the 12th International Symposium on Aviation Psychology.* Dayton, OH: Wright State University.

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Thomas, L. C., & Wickens, C. D. (2005). Effects of CDTI display dimensionality and conflict geometry on conflict resolution performance. *Proceedings of the 13th International Symposium on Aviation Psychology*. Wright-Patterson AFB, Dayton, OH.

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